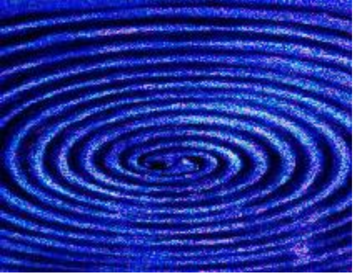
Cosmology with Gravitational Wave Standard Sirens

Ray Frey

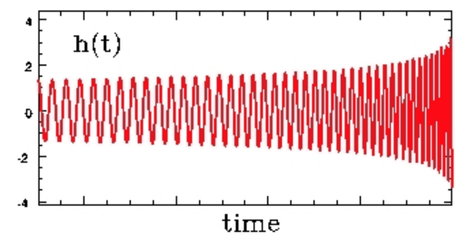
Neal Dalal, Daniel Holz

Relevant papers: arXiv:1105.3184, arXiv:1108.6056, arXiv:1210.6362

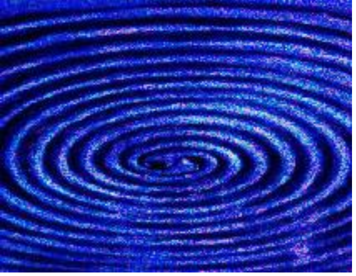


Standard Sirens

- Measurement of GWs from inspiraling binaries (NS-NS, NS-BH, BH-BH) can provide **absolutely calibrated** distance (Schutz 1986)
  - like SNIa, measures luminosity distance d_L
  - unlike SNIa, no calibration uncertainty. No distance ladder. d_L is measured in Mpc (not h^{-1} Mpc). NO astrophysical systematics
- Basic idea: from GWs, measure *both*:
  - frequency chirp ⇒ total power in GW radiation
  - strain h_{ij} ⇒ infer GW flux at Earth

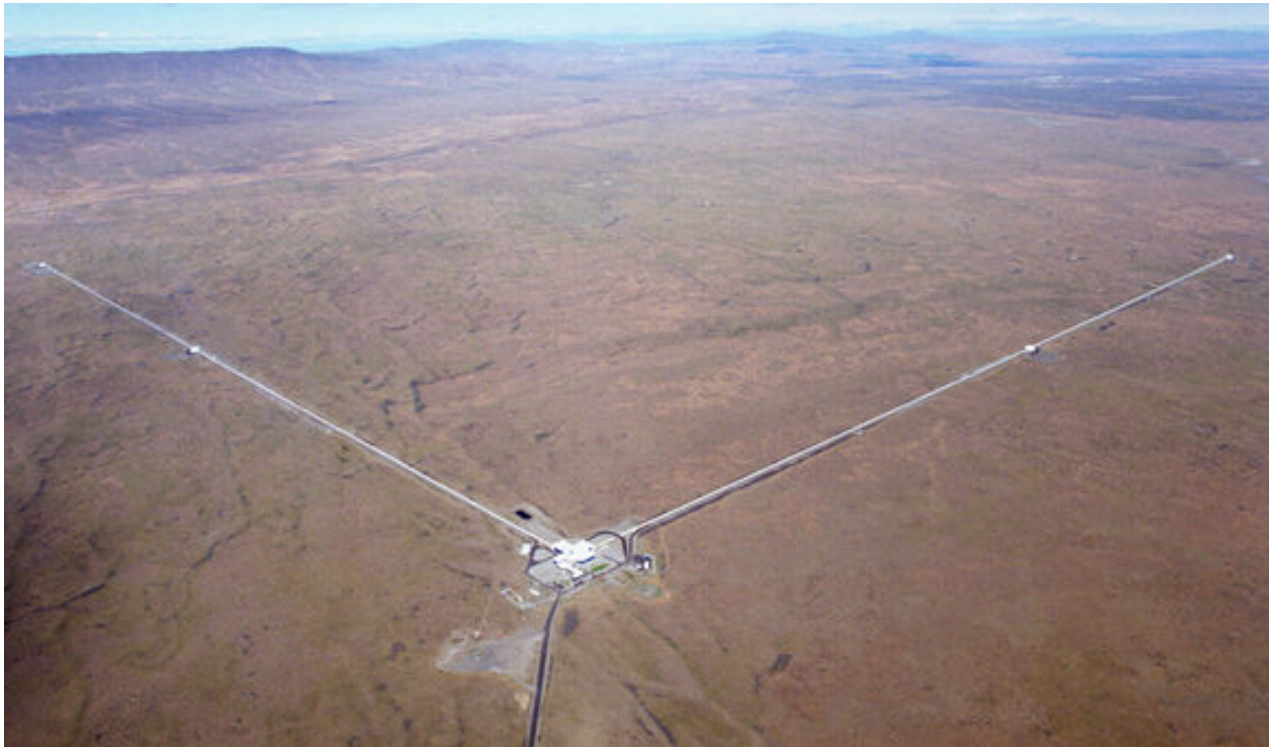


- Ratio of luminosity/flux gives distance d_L



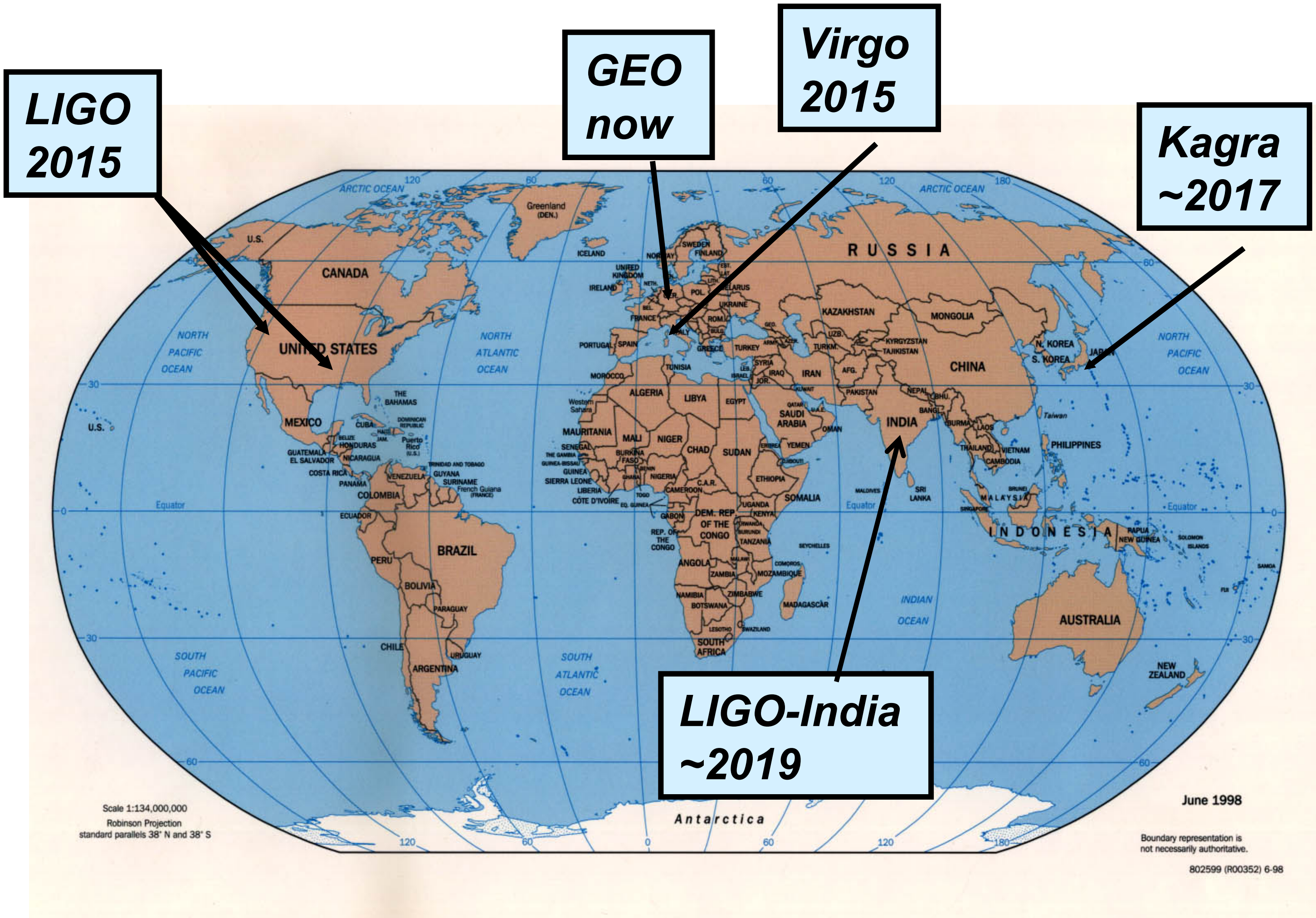
GW Detectors

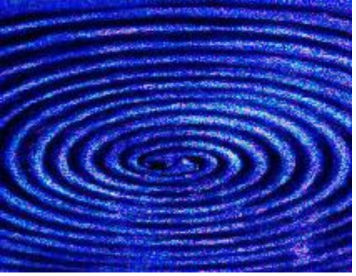
- Ground-based:
  - LIGO:
    - 2 detectors, in Livingston LA and Hanford WA
    - upgrade to aLIGO : 2015
  - Virgo (France/Italy)
  - KAGRA (Japan)
  - LIGO-India?



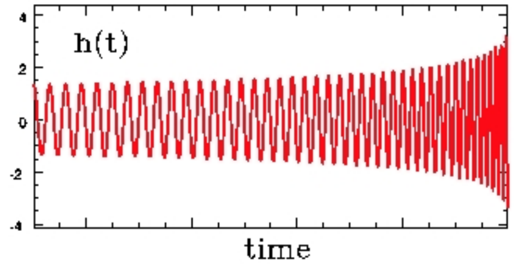
- Satellite:
  - eLISA: ???

The 2nd generation GW detector network



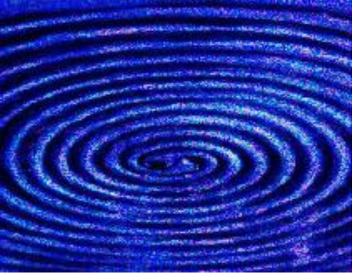


Sources



- ground-based GW detector networks (e.g. LIGO +Virgo+Kagra) are sensitive to nearby stellar mass BNS, NS-BH, BBH inspirals, $z \lesssim 0.2$.
  - too close to measure dark energy, but instead will constrain Hubble constant H_0
  - relevant frequencies: $f \approx$1-10 Hz to kHz, events are in band for $\sim$ minutes

- satellite missions (eLISA) probe supermassive black hole mergers out to high redshift (z~2)
  - relevant frequencies: $f \approx$ mHz, sources in band for $\sim$ year



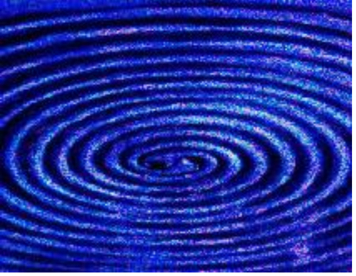
Compact binary coalescence: expected rates

arXiv: 1003.2480 ,
CQG, (LSC, Virgo)

TABLE V: Detection rates for compact binary coalescence sources.

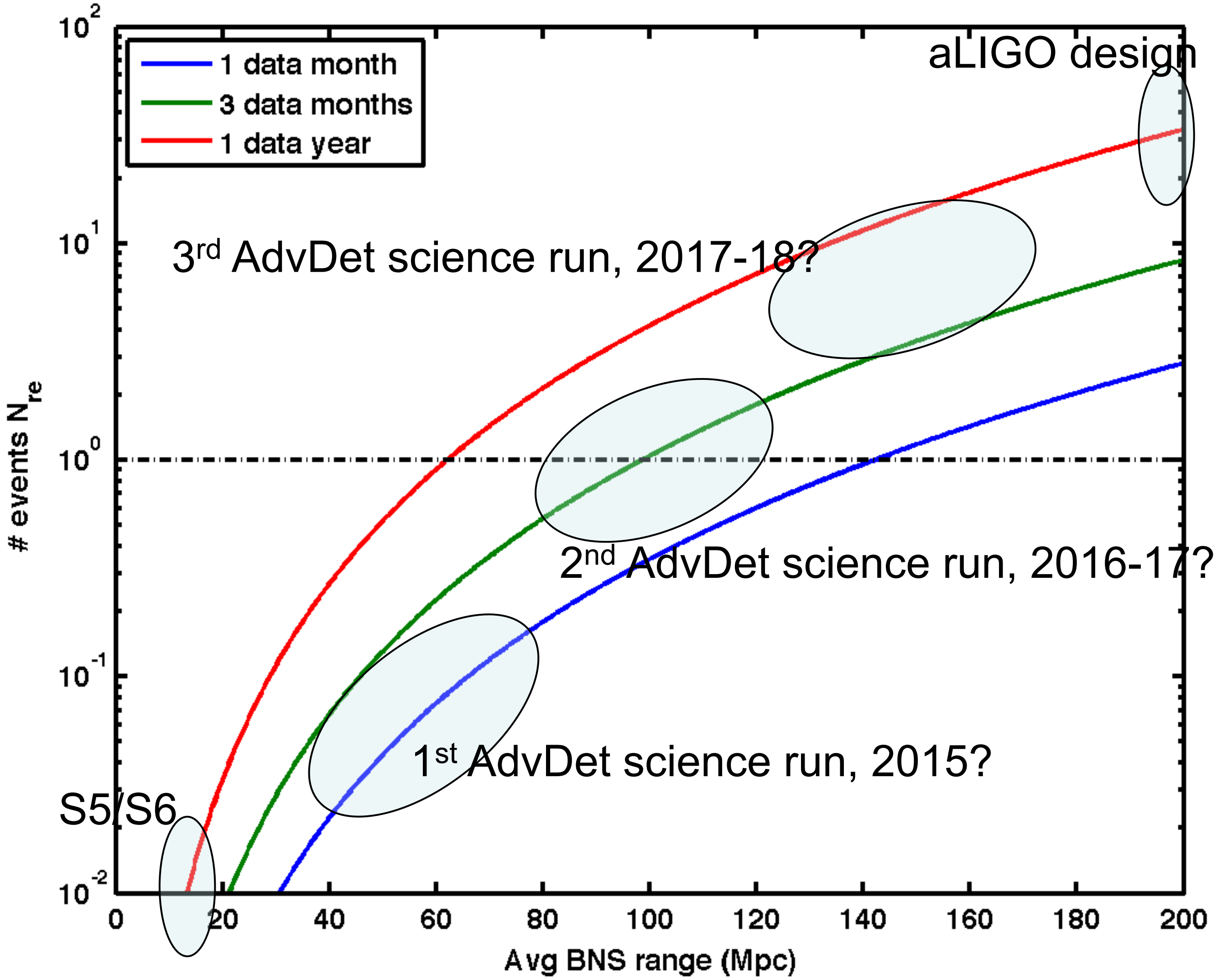
IFO	Source[a]	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm high}$ yr^{-1}	$\dot{N}_{\rm max}$ yr^{-1}
Initial	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			< 0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]
Advanced	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
	BH-BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

Short GRB rates consistent with this.
But also uncertain (due to beaming angle)
Fong and Berger, arXiv:1204.5475



Projected Advanced LIGO BNS Detection Rates

$$N_{re} = \frac{T_{obs}}{\mathrm{Mpc^3 Myr}} \times \frac{4}{3}\pi D^3_{avg,BNS}$$

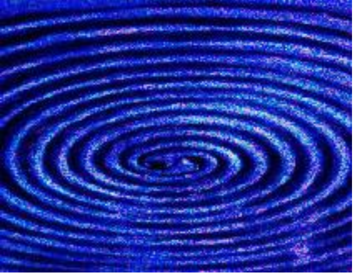


by permission of
G. Gonzalez,
AAS 2013

Limitations

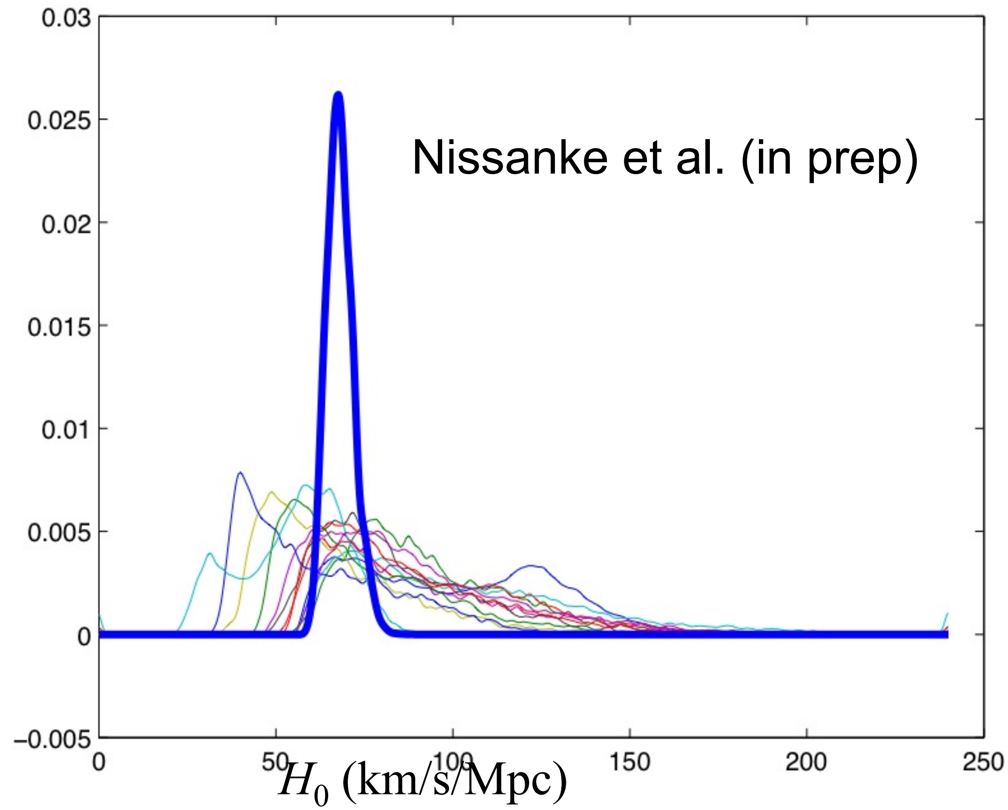
- Since GW emission is not isotropic, we need to know the inclination of orbital plane to measure distance
  - can infer this from GW *polarization* – requires 2 or more non-aligned detectors (e.g. LIGO + (Virgo or Kagra or LIGO-India)
  - Or infer from beaming for short GRBs due to binary mergers

- Since GR is scale free, GW provide no redshift information
  - we therefore require an independent measurement of redshift, from EM emission

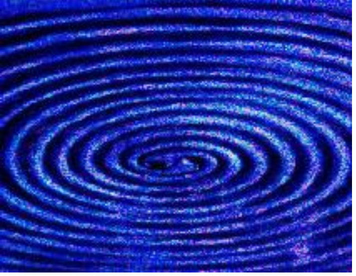


Distance forecasts

- expect fractional errors on H_0 of ~ 0.05 $(N/10)^{-1/2}$ for N events, using 3-detector ground-based network
- Number of detected events increases significantly as size of network increases
- Smaller errors for eLISA sources. Noise is dominated by gravitational lensing



A precision measurement of the Hubble constant,coupled with constraints at high redshift from the CMB, give a tremendous lever arm to measure properties of the dark energy equation of state. Measuring H0 removes a key uncertainty currently limiting our knowledge of the dark energy equation-of-state.

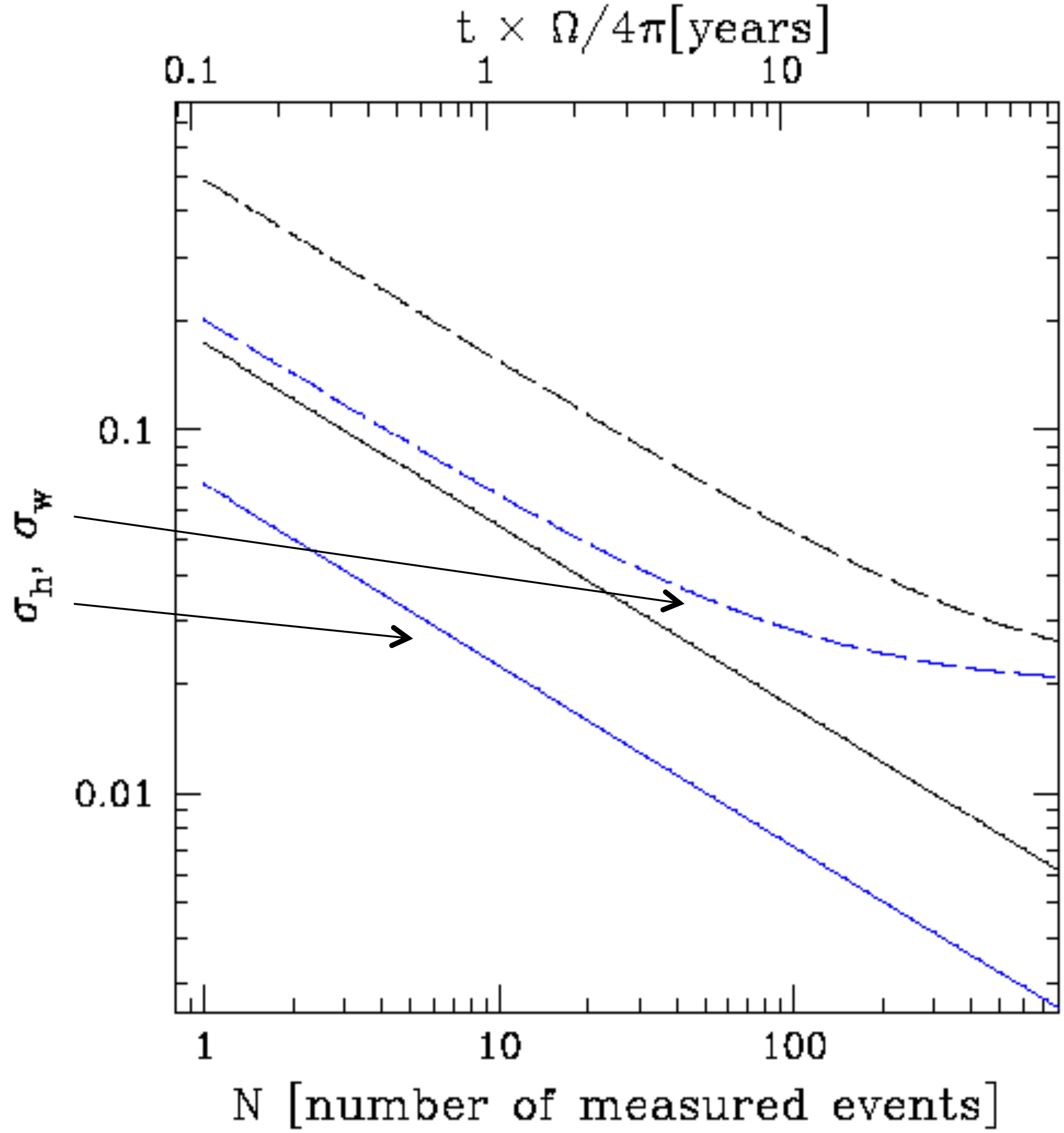


DE Sensitivity

To gauge the sensitivity to the DE EOS, Dalal et al calculated the error on H0 and w as a function of the number of BNS events.

Assumptions:

- 1% CMB $\Omega_m h^2$
- flat universe
- w constant

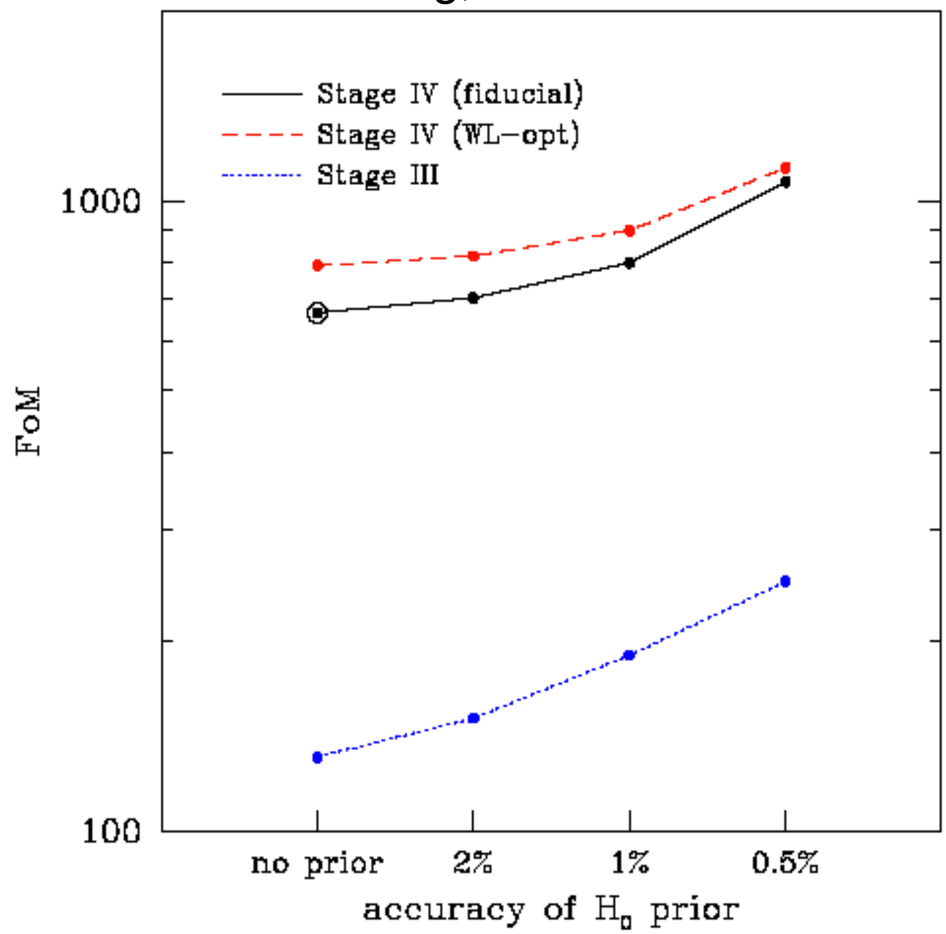


Role of precision H0

- Precision H0 will aid other DE probes
- FOM from DETF

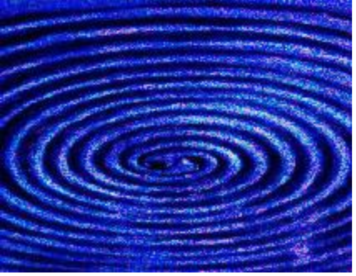
- From Weinberg et al. (2012):
  - *Assuming a w0 − w_a model for dark energy, a 1% H0 measurement would raise the DETF Figure of Merit by 40%*
  - *A precise determination of H0, coupled to a w(z) parameterization that allows low-redshift variation, could … definitively answer the basic question, "Is the universe still accelerating?"*

Weinberg, et al. 2012



EM counterparts

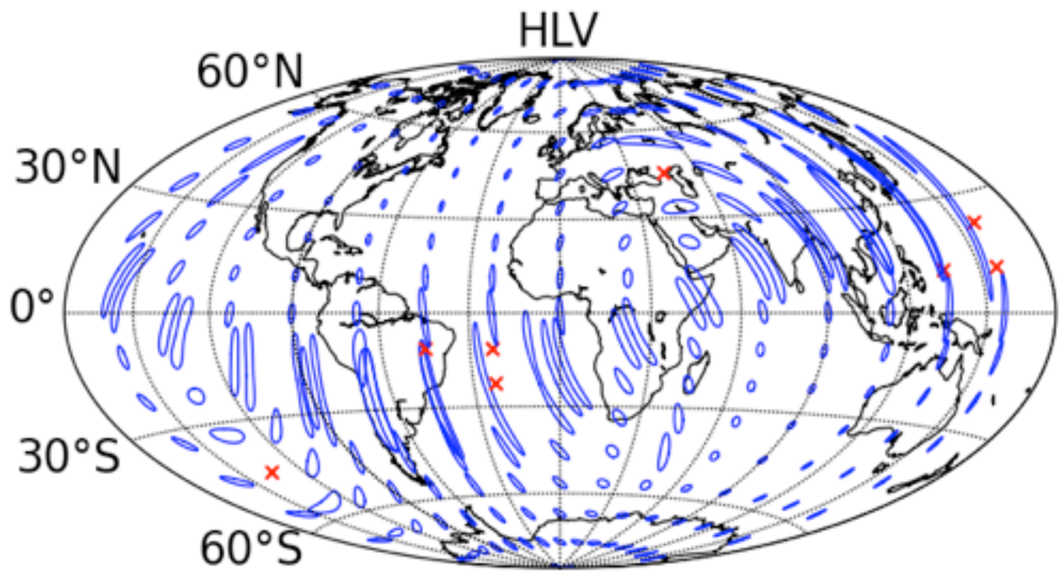
- Need redshifts to measure H0
- Requires independent observations of any EM emission
- Two possibilities:
  - independent trigger (e.g. GRB detection from all-sky γ-ray satellite) provides space-time coordinates for GW search
  - follow-up of GW trigger
    - e.g. off-axis GRB afterglow or isotropic *kilonova* afterglow
- Follow-up of GW sources requires good *localization* on the sky



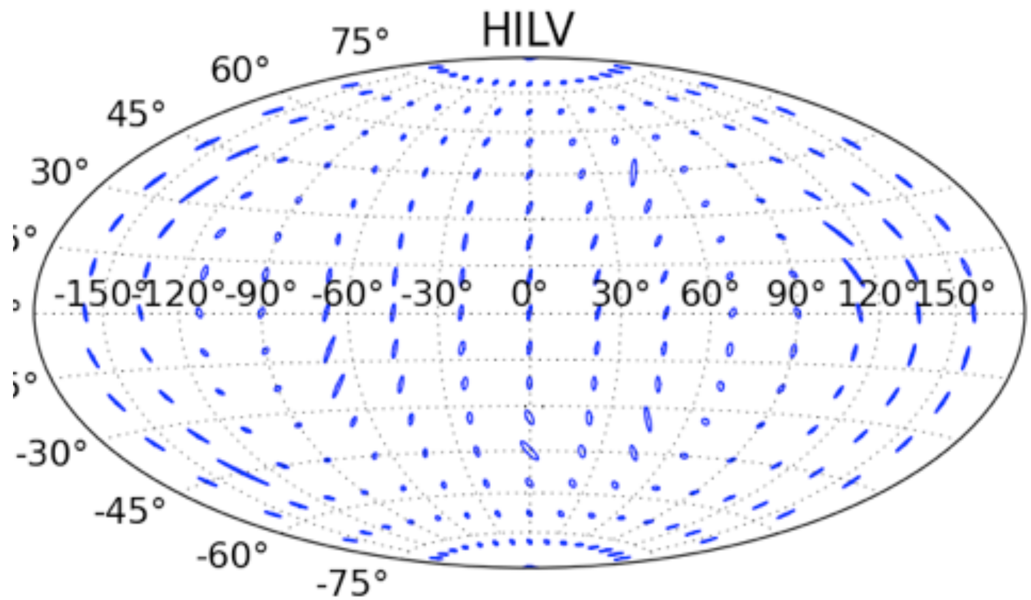
Localization

NS-NS binary inspirals

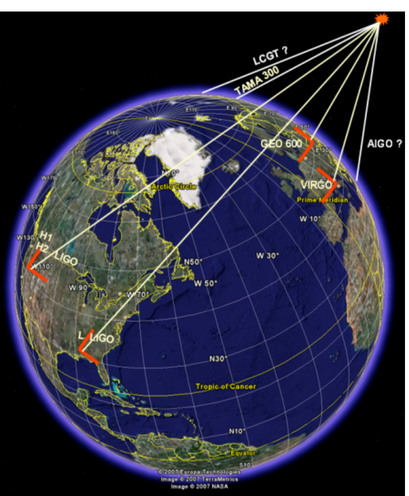
Fairhurst et al., arXiv:0908.2356; 1010.6192; 1205.6611



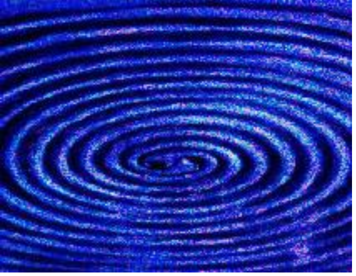
LIGO-Virgo



LIGO-Virgo + LIGO India

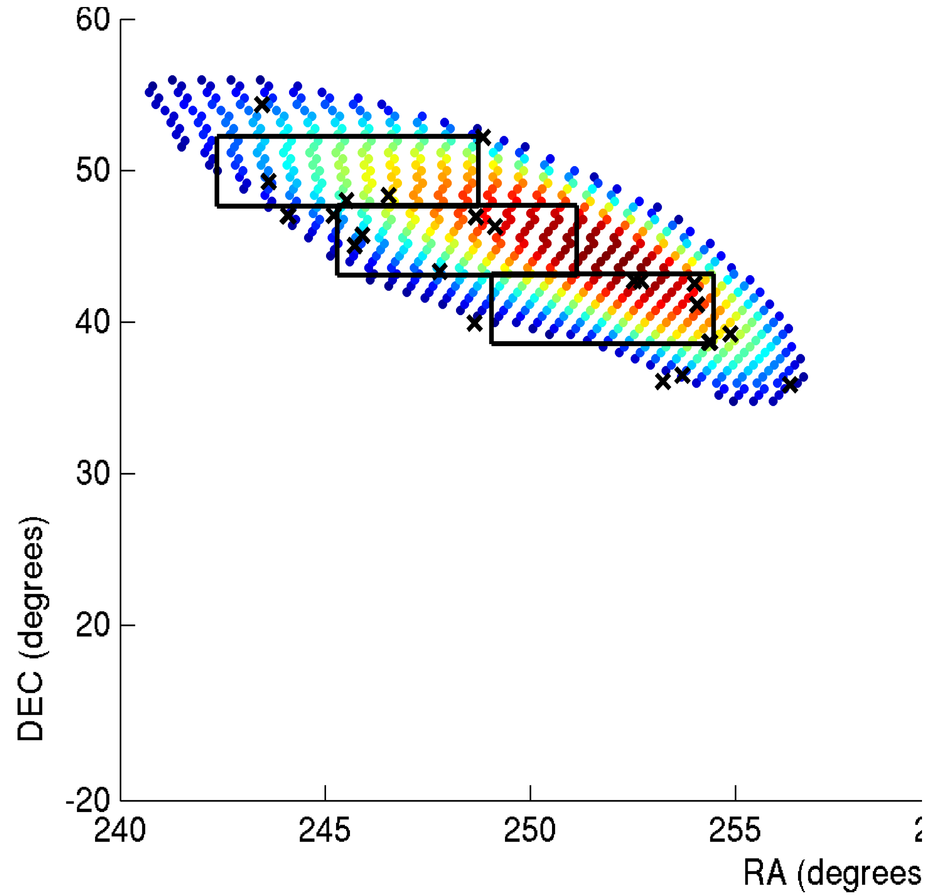


For 4-element networks expect ~ 10 deg^2



Identifying EM counterparts

- EM follow-up (optical, X-ray, radio…) must tile the GW error box
- However, we expect the EM flux to fade quickly (reach r>24 in ~ day)
- need to cover error box quickly ⇒ need fast, wide-area imagers



e.g. see analysis by Metzger & Berger **arXiv:1108.6056**

Wide-field imaging

- This requires target-of-opportunity imaging on observatories with large etendue
  - LSST obviously ideal. Reaches r ≈ 24.5 in 15 seconds over 9.6 deg^2 FOV, so it can cover error box within minutes
  - but other wide-area imagers may be adequate, e.g. DECam reaches r ≈ 24.5 in < 2 minutes over 3 deg^2 FOV, so it can cover error box within hours. HSC even faster (and is in the North, so it's complementary)
  - **BUT**: we don't know how faint the optical emission will be. If much fainter than GRB afterglows, then LSST ToO may be necessary.
  - the broader the latitude & longitude coverage, the higher the fraction of events that are followed up

Summary

- GW measurements of compact binary mergers at low z …
  - provide check of distance ladder
  - with enough events provide precision H0 measurement which, when combined with other measurements, improves DE constraints
- Requires independent observations of any EM emission
  - Short GRB-triggered GW search
  - GW-triggered EM followup

- Expect the experimental program to bring results during the period 2015-2020